# DECADE PERFORMANCE OF A ROOF-MOUNTED PHOTOVOLTAIC ARRAY

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**ABSTRACT**

The Georgia Institute of Technology's Aquatic's Center is equipped with a 342kW roof-mounted photovoltaic array. This array will reach its ten year anniversary in July of 2006. It is therefore an appropriate time to review its performance. This system is closely monitored and studied with the help of a data acquisition system. Data collected from this system is stored and analyzed. Meteorogical parameters such as plane of array insolation are analyzed and compared with predicted values. Additionally, system parameters such as AC energy production, system efficiency, and module temperature are also monitored. The relationship between certain parameters, such as inverter efficiency and inverter loading, are also examined. With the collected data, the reliability of the system may be analyzed using data from system downtimes. From the analysis, we conclude that the system is operating well and in line with expectations.

## 1. Introduction: The Aquatic Center PV System

The 342 kW photovoltaic (PV) system at Georgia Tech's Aquatic Center will have its ten year anniversary in July of this year (2006). When it was first deployed, the array was the largest roof-top PV installation in the world, containing 2,856 multicrystalline silicon modules, with an area of 3175 $m^2$. The modules are flush-mounted with the roof of the Aquatic Center, which is curved, giving the modules a tilt range of $13^o$ south-facing to $10^o$ north-facing. Groups of 12 modules are connected in series, called "strings." In total there are 238 strings connected in parallel. This configuration supplies 810 $A_{DC}$ at 410 $V_{DC}$ (rated values) via seven feeder circuits and a power conditioning unit (PCU) to the Aquatic Center and the distribution network it is connected to.

The PCU performs multiple functions. It is rated at 315 $kW_{DC,}$ and inverts this power to AC. In addition, the unit performs maximum power point tracking, and contains protection functions such as anti-islanding using under/over frequency and under/over voltage relays, and ground fault current interruption. The AC power is fed through a delta-wye isolation transformer into the grid.

## 2. The DAS monitoring the Aquatic Center PV system

Monitoring of the PV system is performed with a Campbell Scientific CRX10 data acquisition system (DAS), which collects snapshots of system data every 10 seconds. Various system performance data are collected, including DC power, real and reactive AC power, voltage and current, as well as meteorogical parameters such as plane of array insolation, ambient and module temperatures, and wind speed. This data is averaged every 10 minutes and stored in two data loggers, one located on the roof, and the other in the inverter room. Real-time data is published on the website of the UCEP at Georgia Tech at (http://www.ece.gatech.edu/research/UCEP/), and logged data is processed and stored on a server.

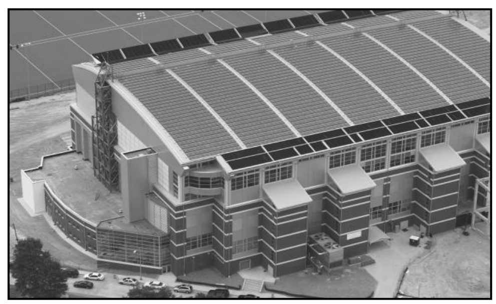

Fig. 1. Aquatic Center Roof-Top PV Array

## 3. Performance Data

Various performance data are extracted from the chronological data records. This section contains data and plots for the PV system as the ten year anniversary approaches. Below is a table summarizing several operating parameters for the system over its entire lifetime.

Table 1. Summary of System Operating Parameters

| | |
|---|---|
| Typical PV Array $V_{DC}$ Range | 340-420V |
| AC Energy Produced (as of April 1, 2006) | 3001.3 MWh |
| Max. Mean Module Temp. Recorded | 46.6°C |
| Max. Monthly AC Power Recorded | 46.4 MWh |
| System Operational Hours | 85,416 hours |
| System Down Time Hours | 11,013.2 hours |

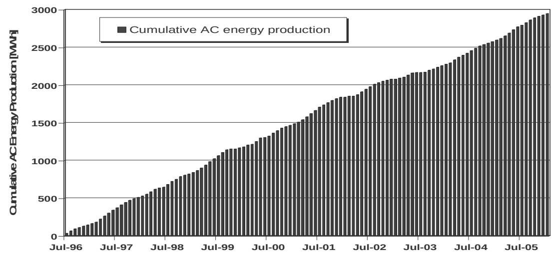


Fig. 3. Cumulative AC Energy in MWh from 07/96–04/06.

Figure 3 shows the cumulative energy production for the system. As of April 1, 2006, the system has produced 3001.3 MWh of AC Energy.

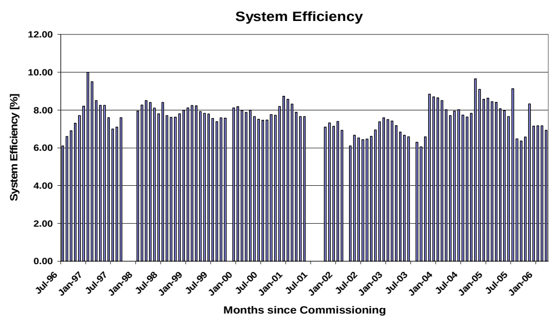


Fig. 4. System Efficiency [%] from Jul 96 – April 06.

Figure 4 shows the efficiency the system operated at throughout the past ten years. As expected, the efficiency changes with season, becoming larger during winter months, and smaller during summer. Because of building construction and various other downtimes, several efficiency values are missing.

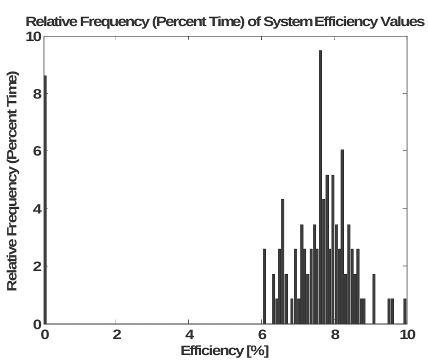


Fig. 5. Histogram of System Efficiency [%].

Relative frequency, or the percent time the system spends at a particular operating condition, of efficiencies is shown in Figure 5 above. It can be seen that the system most often operates within a band of 7-9% efficiency.

Figure 6 shows inverter efficiency versus fractional loading (the fraction of rated power which the inverter is producing). As is expected, the inverter is more efficient when operating at higher loads. There are several data points that stray from the trend at approximately 0.1 fractional loading. This data is from the year 2001 in which several modules were damaged (stray bullets).

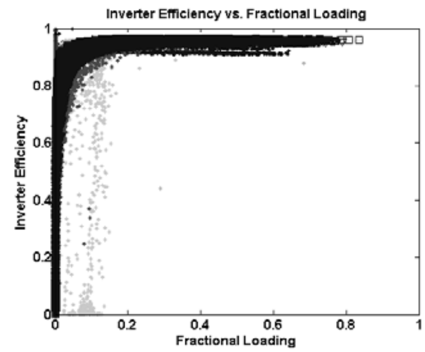


Fig. 6. Inverter Efficiency, as a fraction of nominal power capacity, versus Fractional Loading.

From Figure 7 below, the solar energy flux on the roof of the Aquatics Center is most often between 2 to 3 kWh/m$^2$/day, and next most often between 5 and 6 kWh/m$^2$/day.

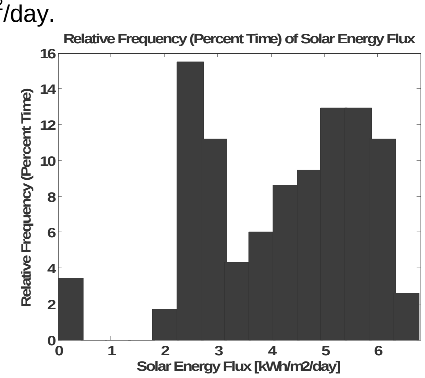


Fig. 7. Histogram of Daily Solar Energy Flux (in kWh/m$^2$/day) for Lifetime of the Installation.

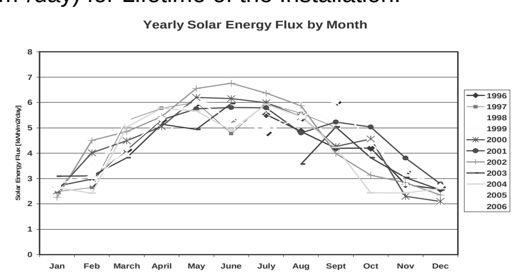


Fig. 8. Monthly Averages of Daily Solar Energy Flux in kWh/m$^2$/day (different years are labeled differently)

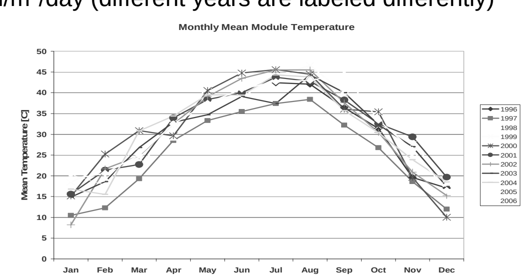


Fig. 9. Mean Monthly Module Temperatures in C$^o$ (different years are labeled differently)

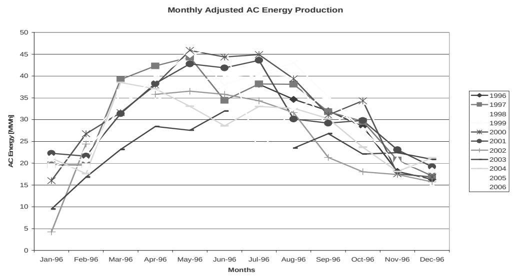


Fig. 10. Adjusted Monthly AC Energy Production in MWh.

The combination of Figures 8 through 10 illustrate how energy production typically peaks in late spring and early summer for the Atlanta location. With peaking solar energy flux and lower module temperature during May, the energy production peaks. It should be noted that higher module temperatures lead to lower efficiencies. Figure 10 is adjusted for downtime. This is done by interpolating expected AC Energy Production for times when the system is not operating.

Figure 11 below shows how often the PV system produces various monthly AC energy values. This is broken down to hourly AC energy values for the first year of operation, and for the year 2005 in Figure 12. This figure shows zero AC energy production to be most frequent due to non-daylight hours. The first year of operation produced a total of 332 MWh of energy where the year 2005 produced 353.6 MWh.

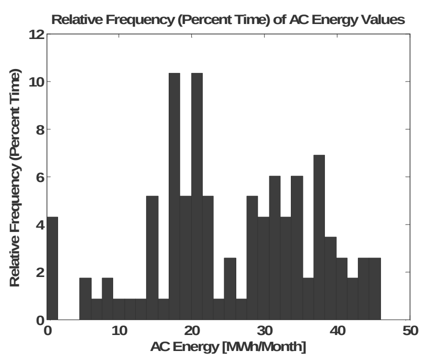


Fig. 11. Histogram of Monthly AC Energy for Lifetime.

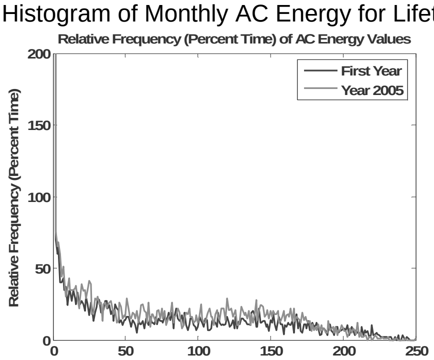


Fig. 12. Histogram of Hourly AC Energy for the First Year and for 2005.

Module temperature varies with season, as can be seen from Figure 13.

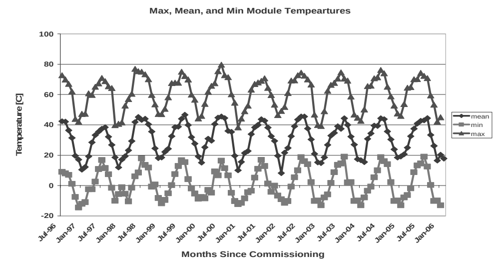


Fig. 13. Monthly Average, Minimum and Maximum Module Temperatures in C$^o$.

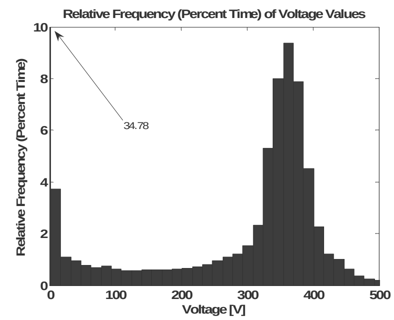


Fig. 14. Histogram of Operating Voltages (Volts) for Lifetime

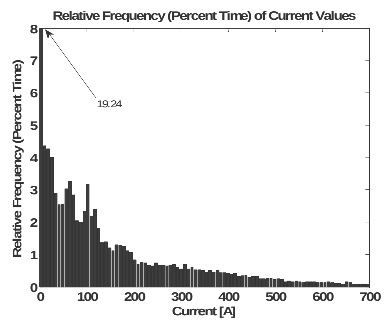


Fig. 15. Histogram of Operating Currents (A) for Lifetime.

Figures 14 and 15 show the percent time the system operates at voltage and current values. Downtime is ignored in these figures, however non-daylight hours are included. Thus, the system most often operates at zero current and voltage values. However the voltage has a concentration of operating at 300-400 $V_{DC}$.

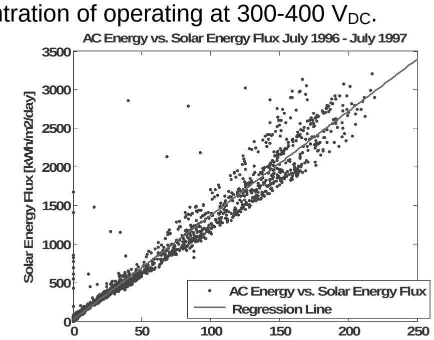


Fig. 16. Daily AC Energy in kWh vs. Daily Solar Energy Flux in kWh/m$^2$/day in the First Year of Operation.

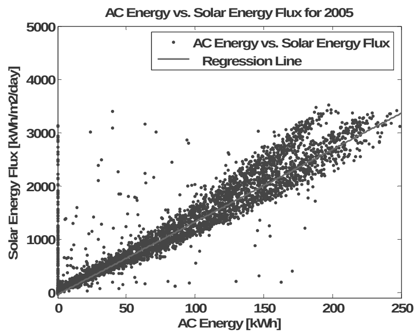


Fig. 17. Daily AC Energy in kWh vs. Average Daily Solar Energy Flux in kWh/m$^2$/day for 2005.

AC energy versus solar energy flux are plotted in Figures 16 and 17 for the first year of operation and for the year 2005 respectively.

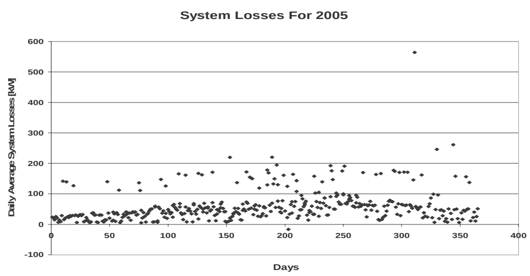


Fig. 18. Daily Average System Losses in kWh for 2005

The losses of the entire PV system, from the modules to the AC side of the PCU are illustrated for the year 2005 in Figure 18.

## 4. Reliability

The reliability of the system is directly related to how often the system is not operating. There are various reasons for downtime. Several major causes are listed in Table 2.

From the above table, the most dominant reason for downtime is construction at the Aquatics Center. In 2003 the building was enclosed, which took the system down for a significant amount of time. The PCU/inverter over temperatures occurred because of a broken fan. It can also be seen that the power electronics is a vulnerable part of the system.

Table 2. Dominant Reasons for Downtime

| Source | Number of Events | Percent of Downtime | Percent of Lifetime |
|---|---|---|---|
| Aquatic Ctr. Construction | 9 | 35.52% | 4.62% |
| PCU/Inverter Over- Temp. | 3 | 23.10% | 3.0% |
| Transducer Failure | 1 | 5.01% | 0.65% |
| Other | 24 | 36.37% | 4.73% |

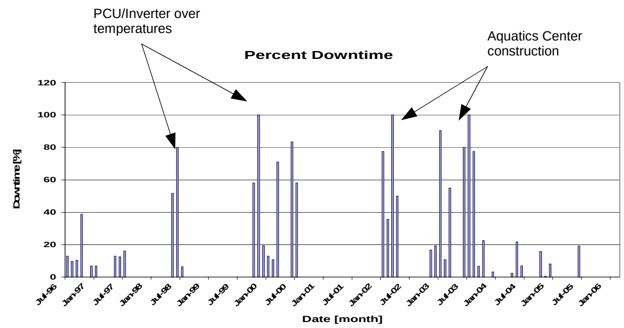


Figure 19: Monthly Percent System Downtime.

Figure 19 illustrates system downtime in percent per month since the commissioning of the system. Arrows point to times when there were PCU/inverter over temperatures, and for times when there was building construction.

## 5. Conclusion

Georgia Tech's Aquatic's Center PV system has been in operation for close to 10 years. Having operated for 1/3 of its expected lifetime, the system has reached a milestone which deserves a thorough performance review. There were no major problems with the system, the only significant weakness being building construction unrelated to the PV system and malfunctions and breakdowns of the power electronics associated with the PCU. The system efficiency appears steady over the years. The system has performed well and has met the expectations, confirming the validity of the design. A major concern are the lengths of repair times following malfunctions, which is attributed to human action. The overall performance should be judged in the light of almost non-existent O&M which the system requires.

## References

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